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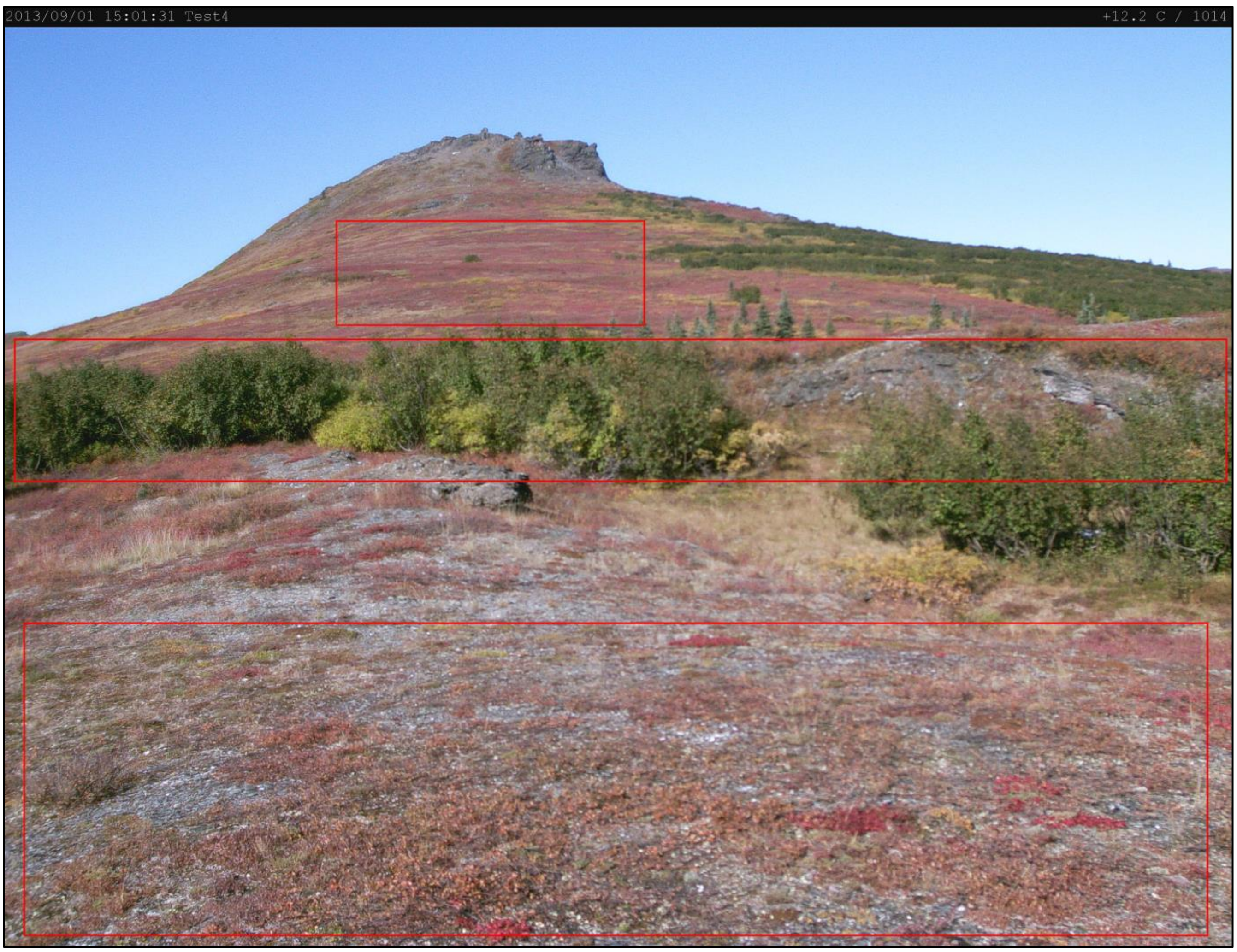
Natural Resource Stewardship and Science

Monitoring of Greenness and Snow Phenology by Remote Automated Cameras in the NPS Arctic Inventory and Monitoring Network, 2013-14

Natural Resource Data Series NPS/ARCN/NRDS—2015/798



ON THE COVER
Salmon River station phenology monitoring windows, 1 Sept 2013. The upper window is the “tundra” window, the middle one “alder”, and the lower one “foreground”. This day was 2 days before maximum redness in 2013 for the “tundra” window and the day of maximum rate of greenness change for the “alder” window.

Monitoring of Greenness and Snow Phenology by Remote Automated Cameras in the NPS Arctic Inventory and Monitoring Network, 2013-14

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Abstract

Remote automated cameras were installed at four climate monitoring stations in the NPS Arctic Inventory and Monitoring Network in 2013. The cameras documented fall senescence and snow establishment in 2013 at all four sites, and spring snowmelt and green-up at one site; the cameras at the other three sites failed to restart after the winter dark period.

Rectangular analysis zones were defined on the photos. Data in the form of digital counts for the red, green and blue color bands were extracted from these zones and analyzed for greenness and snow cover with scripts written in the Python language. Greenness indices were computed from the photo data and fitted with sigmoid curves, rising in the spring and falling in the fall. The fit to a sigmoid curve was quite good, except for the fall in analysis zones dominated by vegetation with strong red fall colors that produced a prominent fall greenness minimum. The midpoint date and rate factor of green-up and senescence were readily obtained from the sigmoid curves. The curves with fall red colors were smoothed by a 1-week moving linear regression, and the greenness minimum (peak redness) was readily located on the smoothed curve. These phenology metrics (the midpoint date and rate factor for green-up and senescence, or fall greenness minimum) will be useful in future study of year-to-year variations and trend analysis.

The snow analysis script was designed to find the optimal pixel brightness value of the blue color band to separate snow and non-snow. The snow classification algorithm used a one-way analysis of variance criterion to locate the two groups of pixels with the strongest possible contrast, and classified the brighter of the two as “snow”. An initial estimate of snow cover was needed to aid in classification of scenes that were mostly snow or mostly non-snow. Snow percent cover derived by this method showed good day-to-day consistency and good fit to a sigmoid curve during spring melt. Snow cover establishment in the fall was described by date of first snow (50% cover or more), and date of first snow that lasted for at least 2 weeks. We anticipated that the 2-week snow cover would last all winter, but exceptional thaw events in 2013 resulted in snow cover loss in October followed shortly by re-establishment at two sites, and less than 50% snow cover at one site (Serpentine Hot Springs) through most of the winter. Similar phenology metrics were obtained for the sigmoid curves fit to snow cover as for greenness: the midpoint date in snow loss and a snow loss rate factor.

Acknowledgments

Thanks to Ken Hill and Pam Sousanes for installing and maintaining the phenology cameras as a part of their work on the ARCN Climate and Weather monitoring vital sign, and to Ken Hill and Jim Lawler for helpful comments on this manuscript.

Introduction

Automated cameras allow us to monitor phenology at remote sites from a vantage point on the ground. Cameras can be used to monitor vegetation green-up and senescence, and snow cover establishment and loss (Richardson et al 2007, Sonnentag et al. 2012, Sheriff et al. 2010). Camera data can be used as ground truth for satellite measurements of greenness and snow cover, and as long-term records of representative index sites. Cameras can be coupled with weather observations to allow detailed study of the relationship between weather and phenology events. Cameras provide a view of the landscape that closely resembles what a person on the ground would see, and hence the images are useful for animations and other interpretive products.

For vegetation monitoring, an analysis area is defined on the photograph, and the color data from this area are used to compute the greenness of the vegetation through the year. The snow cover in an analysis area can also be estimated by classification of each photo pixel as snow or non-snow. Greenness or fractional snow cover are plotted against date, and the timing of key phenological events in each year are determined. Examination of these phenology metrics across multiple years of data allows us to track year-to-year variability and long-term trends.

The NPS Arctic Inventory and Monitoring Network (ARCN, five NPS units in northern Alaska, Fig. 1) has included phenology monitoring by remote cameras as part of the Terrestrial Landscape Patterns and Dynamics monitoring vital sign (Lawler et al. 2009). Automated cameras are co-located with climate monitoring stations, which makes installation and maintenance more economical, and allows us to directly link phenology to weather observations.

The purpose of the present report is to analyze the first year of data from four phenology cameras in ARCN. Analysis of greenness followed established methods (Richardson et al. 2007, Sonnentag et al. 2012). Methods for the quantitative analysis of snow cover were developed here and are documented in this report.

Methods

Study Sites and Cameras

The climate stations chosen for installation of phenology camera had a homogenous foreground area that could be used for analysis of greenness and local snow cover. Additional background analysis areas are available at some sites; these are especially useful for tracking the decline in spring snow cover.

Campbell Scientific CC5MPX cameras were mounted in the summer of 2013 on the tripods used for climate instruments at 4 climate monitoring sites (Table 1, Figs. 1 and 2). These cameras are designed for year-round outdoor use and were installed with a solar panel and small battery. The expectation was for the cameras to cease functioning due to low power during mid-winter when there is little solar energy available, and then resume with the return of the sun in the spring. Photographs were taken at the full resolution available on the cameras (2592x1944 pixels) and four (at Mt. Noak, Pamichtuk Lake, and Salmon River) or five (Serpentine Hot Springs) photos per day at hourly intervals centered near noon local time. Since solar noon in western Alaska occurs at 14:00 to 15:00 local daylight savings time, the cameras have been re-programmed for future years to center photos around solar noon. The cameras faced generally north to minimize glare from direct sunlight and shadows on distant hillslopes. As a result of this camera orientation, the distant hillslopes used for analysis of snow cover generally face south. Photos were saved in jpg format on an internal Secure Digital (SD) card and retrieved at the annual site maintenance visit.

Table 1. ARCN Phenology Camera Locations

Station Name	AICC ID[1]	Latitude, WGS84	Longitude, WGS84	Elevation, m	NPS unit[2]
Mt. Noak	MNO	67° 08.486	162° 59.672	256	CAKR
Pamichtuk Lake	PAM	67° 45.977	152° 09.854	1019	GAAR
Salmon River	SRW	67° 27.594	159° 50.475	381	NOAT
Serpentine Hot Springs	SRT	65° 51.138	164° 42.469	150	BELA

[1]AICC – Alaska Interagency Coordination Center (of the Alaska Fire Service) weather station identifier. http://fire.ak.blm.gov/wx/wxstart.php?disp=geog.

[2]See Fig. 1 for NPS unit abbreviations

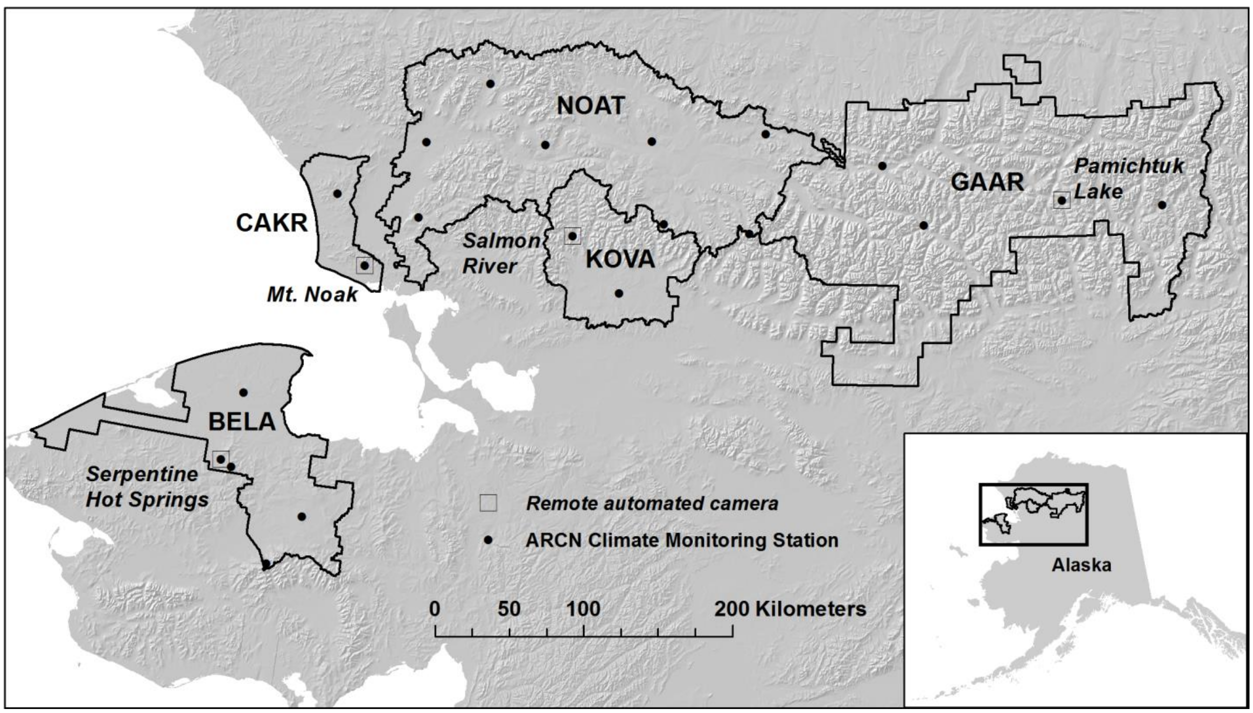

Figure 1. Phenology Cameras Installed in NPS Arctic Inventory and Monitoring Network (ARCN) in 2013.The NPS units in ARCN are the Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and the Noatak National Preserve (NOAT).

Figure 2. Typical phenology camera setup. The camera is the metal cylinder marked with an arrow. Climate monitoring instruments are also attached to the tripod. This is the Serpentine Hot Springs climate station in BELA.

Data Analysis

Analysis Zones

One or more rectangular analysis zones or "windows" were defined on the photos at each station using pixel coordinates (Table 2; all analysis zones are shown on example photographs in the Results). The greenness analysis zones were chosen to encompass an area of relatively uniform vegetation as near as possible to the camera, to minimize the effects of fog, wildfire smoke, and haze. A foreground snow analysis zone, usually the same as the foreground greenness window, was defined to depict snow cover in the immediate vicinity of the station. Where possible, an additional background snow analysis zone was defined to study the snow cover over a larger landscape.

Table 2. Photograph analysis zones

Station	Analysis Zone	Analyses	Description
Mt. Noak	foreground	greenness, snow	*Dryas* (dwarf shrub) tundra, nearly level
Pamichtuk Lake	foreground	greenness, snow	*Dryas* (dwarf shrub) tundra, nearly level
	background	snow	Rounded mountain landscape, south-facing slopes
Salmon River	foreground	snow	Dwarf shrub tundra, gentle southeast facing slopes
	alders	greenness	A band of tall shrubs near the camera, mostly alders (*Alnus*) with some willows (*Salix*)
	tundra	greenness	Birch (*Betula*) shrub tundra on a hillslope at moderate distance from the camera, south-facing
Serpentine Hot Springs	foreground	greenness, snow	Birch (*Betula*) shrub tundra, nearly level
	background	snow	Hills with tussock and low-shrub tundra, mostly south-facing

Camera images were stored as 3 digital counts: numbers between 0 (dark) and 255 (bright) for red, green, and blue (R, G, and B) of each pixel. A script written in the Python language using the Python Imaging Library (PIL, Lundh and Ellis 2002) and NumPy (Numpy Developers 2013) was used to extract the data from each pixel in the analysis window to a numerical array and perform computations. These scripts and procedures to run them are in the ARCN monitoring protocol for the vital sign "Terrestrial Landscape Patterns and Dynamics" (Swanson 2015).

Greenness Indices

The data were corrected for differences in illumination (due to clouds, haze, changing sun angle, etc.) by computing greenness indices from the numerical counts of the three color bands. Two greenness indices were used (Richardson et al. 2007, Sonnentag et al. 2012):

"Excess green": $ExG = 2G – (R + B)$

"Percent green": $g\% = 100 * G/(R + G + B)$

These indicates correlate well with one another and with NDVI (a measure of vegetation productivity computed from red, green, and near infrared light; Tucker and Sellers 1986) as measured from the ground or satellite. They also correlate well with on-the-ground measurements of vegetation productivity (Richardson et al. 2007, Westergaard-Nielson et al. 2013). The value for each index was averaged for the analysis zone on each photo. The two greenness indices are somewhat redundant, but they are easily computed and we currently lack criteria to choose one over the other.

Greenness Phenology Metrics

The median of the daily measurements was computed to obtain a single greenness value for each day. The median is less sensitive to rare anomalous values than the mean. This practice differs from that recommended by Sonnentag et al (2012) and adopted by the NPS Northeast Temperate Network (NETN; Tierney et al. 2013), where the 90th percentile value is computed for a 3-day moving window. I chose the median because the ARCN data shows roughly equal scatter in both the high and low directions from a central tendency. In contrast, the NETN data is composed of many frames per day (32) over a longer period (16 hours) and greenness is obviously skewed, with most values clustered near an upper limit, and the low values are anomalous. In our data illumination conditions are usually quite similar for all 4 or 5 daily frames, e.g., all sunny or all foggy, and all are within 4or 5 hours at mid-day, so the daily median provides a good summary for the daily values. At the ARCN sites there is no simple relationship between time of day or cloud cover and the greenness index on the photos. Greenness on photos taken close in time (i.e. photos with similar vegetation characteristics) varies in a complex fashion with the way light is filtered and scattered from clear sky, different types of clouds, haze, and wildfire smoke. This day-to-day variability is dealt with by the curve-fitting procedure described below, allowing extraction of phenology metrics from the curves.

Fog and clouds are generally not a problem for the foreground windows used for greenness analysis. However, a few photo frames where the entire lens was foggy, or where a mid-range analysis window (e.g. Salmon River, tundra) was obscured by clouds or fog, were eliminated manually from the analysis.

Our objective was to find the dates that best characterize the timing of green-up and senescence at each station each year. To accomplish this I fit a sigmoid curve to the data after Richardson et al. (2007):

$$y = a + \frac{b}{1 + e^{c(d-x)}}$$

where y is the daily median greenness of the analysis zone, x is the ordinal date (expressed as a number from 1 to 365), and a, b, c, and d are constants (Fig. 3). The constant d is of greatest interest, as it can be used to quantify changes in the timing of green-up or senescence between years. The rate constant c can be used to compare the rate of green-up or senescence between years or sites. This constant has units of days^{-1} and alone is difficult to interpret, but if we choose representative start and end positions on the curve, it can be converted into a time interval in days that represents the length of the green-up or senescence season. Here we use the number of days between 10% and 90% green-up, i.e. the interval between points on the curve where $y_1 = a + 0.1b$ and $y_2 = a + 0.9b$ (Fig. 3). Substituting these y values into the equation above, we obtain the quantity $4.394/c$. For example, if $c = 0.2$, the time interval in days between points with 10% and 90% of total green-up is $4.394/0.2 = 22$ days. This interval is centered over the point of most rapid change (day d, the midpoint); the rate of change declines in both directions from the midpoint down to a rate 0.36 of the maximum at both ends of the 0.1 to 0.9 interval. An analogous time interval with y declining from $y = 0.9b$ to $y = 0.1b$ was used to quantify the rate of senescence and snow cover loss

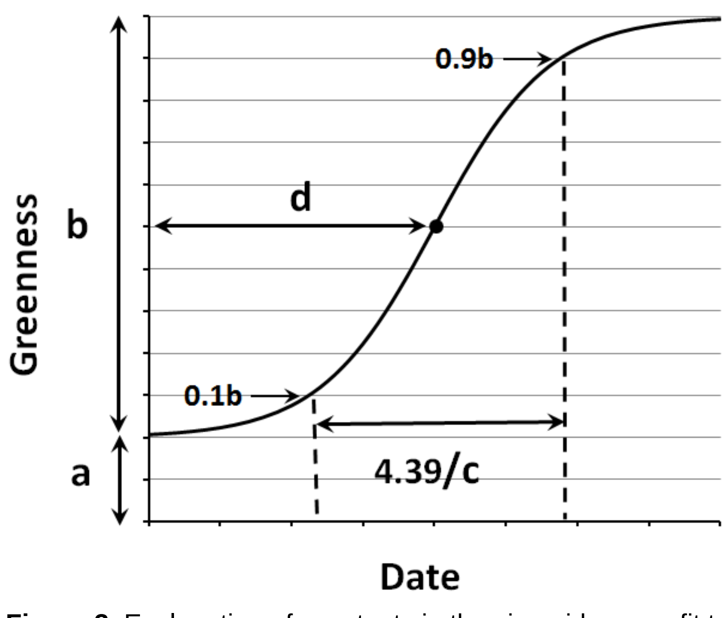

Figure 3. Explanation of constants in the sigmoid curves fit to greenness and snow cover data. The constant *a* is the value of greenness before the change (green-up, senescence, or snowmelt), *b* is the amplitude of change, *c* determines the steepness of the change, and *d* is the ordinal date at the midpoint of the change. The constant *b* is positive for a rising curve (green-up) and negative for a descending curve (senescence or snowmelt).

Curve fitting was by successive approximation using the "nlm" (non-linear minimization) function in the R statistical software (R Core Team 2014). The R scripts for curve fitting and plotting are available in the ARCN monitoring protocol for the vital sign "Terrestrial Landscape Patterns and Dynamics" (Swanson 2015).

Some analysis windows are dominated by tundra plants that have strong red senescence colors. The greenness in these cases does not follow a sigmoid pattern, but instead shows a steep decline to a distinct minimum that represents maximum red colors, followed by a recovery of greenness back to a level below the summer value but well above the minimum. In these cases we use the day of minimum greenness (corresponding to maximum of red fall colors) to quantify the timing of senescence. Due to the scatter in the data, smoothing is required to locate the fall minimum in greenness. Daily medians are smoothed by the least-squares method (Swets et al. 1999, Schwartz and Hanes 2010, Zhu et al. 2013): a linear regression (greenness index vs. date) is computed for a 1-week period centered at each date, and greenness value predicted by the regression for the center date is used as the smoothed value.

Snow Cover Mapping on Photographs

The pixels data extracted from the photos using the Python script described previously was processed by a second Python script to classify each pixel in the analysis window as snow or non-snow. (See Swanson 2015 for the scripts.) Before snow classification analysis, a mask was applied to remove unwanted areas of foreground or sky from some the rectangular analysis windows.

Snow brightness and hue varies greatly between photos, but in any given scene snow is usually lighter-colored than non-snow, and this is especially true for the blue digital band. Non-snow areas tend to be both darker and browner than adjacent snow areas, and brown tones result when red and green digital counts are higher than blue. Thus the blue color band is most useful for identifying and mapping snow.

In most partly snow-covered scenes, the two features of greatest contrast in the scene are light-colored snowy areas and darker colored non-snow areas. Thus to map snow on photographs, an algorithm was developed that searches an analysis window for the blue digital count value that best separates the pixels into two distinct groups. The criterion used to judge the distinctness of the two groups produced by any given “breakpoint” blue value is analogous to a one-way analysis of variance (AOV). The algorithm searches for the breakpoint value that maximizes the ratio of the "between-groups" to "within-groups" mean square deviation. The brighter of the two resulting groups is then classified as snow and the darker group as non-snow.

This algorithm works well for scenes that are about half snow and half non-snow. In a scene with just a few percent of snow area, the AOV-based algorithm will typically identify a "light" group that contains relatively light-colored ground and the few snow pixels. A similar problem occurs with scenes that are predominantly snow, where dark snow (e.g. shadows on snow) and non-snow are identified as the "dark" group. To deal with this situation, the approximate snow cover value of the analysis window in each photo was estimated manually, and the AOV algorithm was used to refine the estimate, as illustrated in the following example. Consider a scene estimated to have 10% snow cover. The AOV algorithm works best if the set of pixels analyzed is about half snow, so we double the 10% value, add 5% just in case our estimate was too low, to get 25%. The algorithm then searches only the brightest 25% of all pixels in the scene for the 2 natural groups, and the brighter of the two groups is labeled as "snow". The darker group is labeled as "non-snow", along with the 75% of pixels that were excluded because they were darker yet. In other words, the snow cover estimate was used to create a subset of pixels that was about 50/50 snow/non-snow, the optimal conditions for AOV algorithm to succeed. The rule was reversed for windows that were mostly snow. For example, in a window estimated to have 90% snow and 10% non-snow, the algorithm searches the darkest 25% of all pixels to find the breakpoint separating snow from non-snow. In windows estimated to have 40% to 60% snow, the AOV algorithm was applied to all pixels. During the manual photo estimation, I flagged photos where the ground was obscured by clouds or fog, which cannot be differentiated from snow with this process. A map of snow distribution of each scene was produced as a check. An example snow map is given in the Results section.

Snow Cover Phenology Metrics

Establishment of snow cover in the fall typically involves one or more early snowfall and thaw events before establishment of a season-long snow cover. For remote sensing purposes I defined “continuous” snow cover as 50% cover in the window that which persists for 2 weeks or more, following the conventions we use for monitoring snow cover by satellite (Zhu and Lindsay 2013). In ARCN a snow cover that persists for 2 weeks or more in the fall usually persists through the entire winter (Swanson 2014). Thus the key events that we expect to record in the fall are the first date of 50% snow cover, and the first date of 50% snow cover that persists for at least 2 weeks and the rest of the winter. However, in the fall and winter of 2013, unusual weather events produced a more complex pattern of snow establishment that is described in the Results.

Loss of snow cover in the spring is typically a more progressive process that can be fitted with a sigmoid curve of the same type used in greenness monitoring. As in the case of greenness monitoring, the midpoint day of snow cover loss (the constant d in the equation above and Fig. 3) and the rate of snow cover loss (constant c) are important metrics. The number of days between 10% and 90% snow cover loss was computed from $4.394/c$ as described above for greenness.

The curve-fit constant d (midpoint day of snow cover loss in the spring) is comparable to the "end of the continuous snow season" that NPS uses for satellite snow cover monitoring (Zhu and Lindsay 2013, Swanson 2014). The latter is defined as the last day of more than 50% snow cover that is preceded by at least two weeks of continuous snow cover.

Degree-Days

The spring phenology events were compared to the accumulated warmth of the season as quantified by degree-days. Hourly temperature data from each climate stations were used to compute the daily mean temperature. Thaw degree-days are the cumulative sum from the start of the calendar year of the daily mean temperature for all days with mean above 0 °C. The degree-days with a base temperature of 5 °C, which may be meaningful for plants (Wielgolaski 1999) was also computed.

Results

Data Availability

The four cameras began taking pictures in the summer of 2013 (Table 3). The Pamichtuk Lake camera was installed early enough (29 May) to capture most of the 2013green-up. The Mt. Noak, Pamichtuk Lake, and Salmon River cameras recorded fall 2013 senescence and snow cover establishment, but stopped working in November and failed to restart in the spring. The Serpentine Hot Springs camera functioned intermittently through the fall, winter, and spring of 2013-14, with the fewest days of data in the darkest months and none in December. Daily imaging resumed on 19 March 2014 and continued through following the spring and summer.

Thus we have spring 2013 green-up data for Pamichtuk Lake (Table 4); fall 2013 senescence data for all four stations (Table 5); fall 2013 snow cover establishment data for all four stations (Table 6); spring 2014 snow loss data for Serpentine Hot Springs (Table 6); and spring 2014 green-up at Serpentine Hot Springs (Table 4).

Table 3. Dates of Phenology Photography at Four ARCN Climate Stations, 2013-14

Station	Start Date, YYYY_MM_DD	Data Availability[1]	End Date, YYYY_MM_DD
Mt. Noak	2013_06_30	Continuous	2013_11_12
Pamichtuk Lake	2013_05_29	Continuous	2013_11_07
Salmon River	2013_7_18	Continuous	2013_11_17
Serpentine Hot Springs	2013_08_07	Aug: 18 days, Sep: 20 days, Oct: 11 days, Nov: 4 days, Dec: 0 days, Jan: 3 days, Feb: 8 days, March: 16 days, Apr-Aug: all days.	2014_09_03

[1]"Continuous" – all days have photos; for Serpentine Hot Springs, the number of days of photos per month is given

Table 4. Spring Greenness Phenology Data[1].

Station	Window	Year	Midpoint of greenup[2], ordinal and calendar date	Greenup rate factor[3]	10%-90% green-up period, days[4]	Curve fit interval (start-end dates)
			Percent green index / Excess green index			
Pamichtuk	foreground	2013	165 / 164 14 June / 13 June	0.265 / 0.233	16.6 / 18.9	149-191[4]
Serpentine Hot Springs	foreground	2014	165 / 164 14 June / 13 June	0.149 / 0.155	29.5 / 28.3	140-191

[1]Dates are given as ordinal dates (number between 1 and 365) and calendar dates (day-month). The slash separates dates determined by the two different greenness indices: percent green index/excess green index.

[2]Parameter *d* in the sigmoid curve equation, see Methods

[3]Parameter c in the sigmoid curve equation, see Methods

[4]The time interval in days between the points on the sigmoid curve with 10% and 90% of green-up

[4]Data collection began on day 149, at which point no green-up was apparent from inspection of the photos; thus the day 149 value was extrapolated to days 140-148 to allow curve-fitting.

Table 5. Fall Greenness Phenology Data, 2013[1].

Station	Window	Midpoint of senescence or maximum redness Ordinal/calendar date[2]	Sensecence Rate factor[3]	90%-10% greenness period, days[4]	Curve fit interval (start-end ordinal dates)
		Percent green index / Excess green index			
Mt Noak	foreground	233 / 232 21 Aug / 20 Aug	0.221 / 0.226	19.9 / 19.4	197-263
Pamichtuk	foreground	247 / 252 4 Sept, 9 Sept	0.125 / 0.135	35.2 / 32.5	201-294
Salmon River	alders	246 / 246 3 Sept	0.397 / 0.268	11.1 / 16.4	230-265
Salmon River	tundra	246 / 246 3 Sept (max redness)	NA[5]		NA
Serpentine Hot Springs	foreground	251 / 251 8 Sept (max redness)	NA		NA

[1]Dates are given as ordinal dates (number between 1 and 365) and calendar dates (day-month). The slash separates dates determined by the two different greenness indices: percent green index/excess green index.

[2]Parameter *d* in the sigmoid curve equation, see Methods

[3]Parameter c in the sigmoid curve equation, see Methods

[4]The time interval in days between the points on the sigmoid curve with 90% and 10% of initial greenness

[5]NA – not applicable, refers to windows with strong red fall colors where no sigmoid curve was fit

Table 6. Snow Phenology Data for the winter of 2013-14[1]

Station	Window	First visible snow in fall	Start of continuous snow cover >50%, >2 weeks	Spring melt midpoint day number (date)[2]	Spring melt rate factor[3]	90%-10% snow cover loss period, days[4]	Curve fit interval (start-end dates)
Mt Noak	foreground	Day 242 30 Aug	Day 266 (23 Sept) thru 285 (12 Oct) then day 298 (25 Oct)	ND[5]	ND		ND
Pamichtuk	foreground	Day 246 3 Sept	Day 266 (23 Sept) thru 290 (17 Oct), then day 293 (20 Oct)	ND	ND		ND
Pamichtuk	background	Day 262 19 Sept	Day 297 24 Oct	ND	ND		ND
Salmon River	foreground	Day 242 30 Aug	Day 266 23 Sept	ND	ND		ND
Serpentine Hot Springs	foreground	Day 242 30 Aug	Day 65 of yr 2014 6 Mar 2014	Day 115 25 Apr	0.481	9.1	95-135
Serpentine Hot Springs	background	Day 242 30 Aug	Day 65 of yr 2014 6 Mar 2014	Day 112 22 Apr	0.200	22.0	75-155

[1]Dates are given as ordinal dates (number between 1 and 365) and calendar dates (day month).

[2]Parameter *d* in the sigmoid curve equation, see Methods

[3]Parameter c in the sigmoid curve equation, see Methods

[4]The time interval in days between the points on the sigmoid curve with 90% and 10% snow cover.

[5]ND – no data because the camera was not functioning during this time

Mt Noak

Greenness

The Mt. Noak camera was tilted between 15 and 16 July 2013 (Fig. 4). Analysis for fall 2013 was performed on the tilted scene, and the camera was reset at the next visit (July 2014). Greenness declined gradually in this patch of *Dryas* tundra through August, with no red color minimum (Fig. 5). The two greenness measures provided similar senescence midpoint dates (20-21 Aug 2013) and rates (19 to 20 days were required to go from 90% and 10% greenness; Table 5)

Snow

Snow cover was analyzed in the same foreground window as greenness phenology. No background window was analyzed. The first snow came on 30 Aug 2013 (day 242; Table 6) and melted by the following morning. Persistent snow arrived 23 Sept (day 266), but it only lasted through 12 Oct. Persistent snow came again on 25 Oct (day 298) and lasted through the end of the period of record (12 Nov 2013). The foreground camera view slopes very gently to the east.

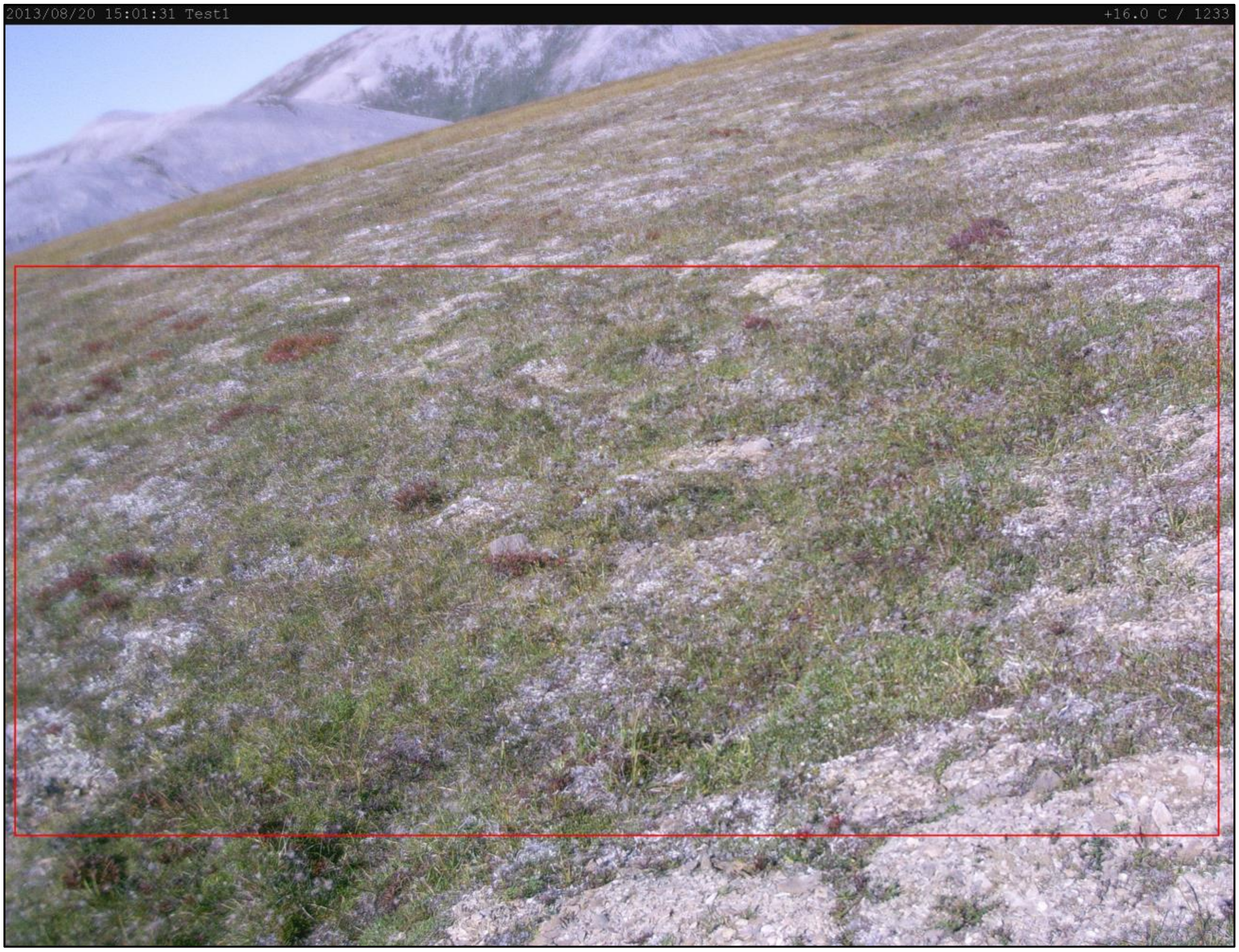

Figure 4. Mount Noak station phenology monitoring window, 20 Aug 2013. This date was identified as the midpoint of fall 2013 senescence. The camera was tilted in July 2013 and reset to level during the next visit (July 2014). The tilted scene was used for fall 2013 phenology.

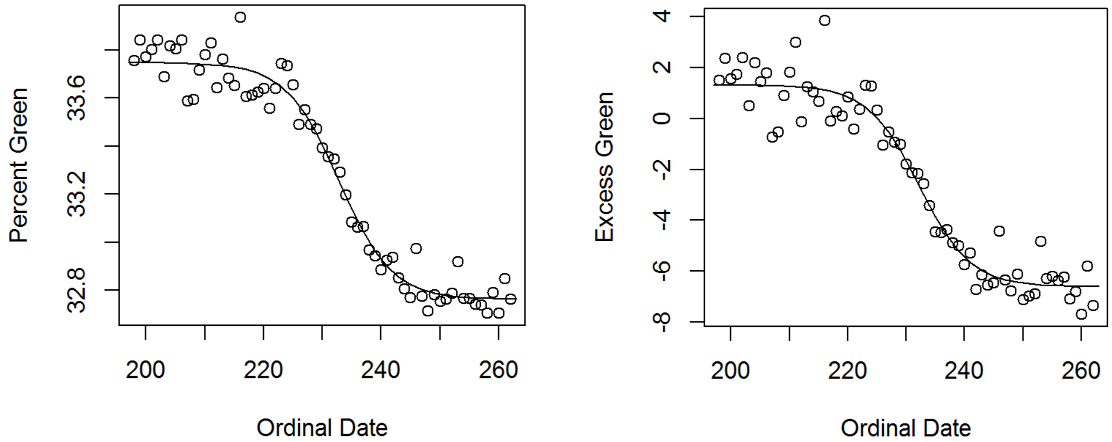

Figure 5. Fall 2013 greenness for the Mt. Noak monitoring station, foreground window. The curve parameters (see Methods) for the “percent green” curve (left) are a = 33.75 (starting value), b = -0.99 (amplitude of change), c = 0.221 (rate constant), d = 232.9 (ordinal date of midpoint of change). The r^2 value is 0.97. The curve parameters for the “excess green” curve (right) are a = 1.32, b = -7.93, c = 0.226, d = 232.2, r^2 = 0.94.

Pamichtuk

Greenness

Early installation of this camera allowed us to capture most of the green-up and all of the senescence in 2013 at this site, which has low *Dryas* tundra similar to Mt. Noak (Fig. 6, Tables 4 and 5). The photos from the record start date (149, 29 May) show no apparent greenness, i.e. this date must be near the start of green-up. However, the curve-fitting algorithm performed poorly without an initial period of low values. Thus the first value (day 149) was repeated back to day 140 to facilitate curve-fitting, and the results are considered tentative. The curve suggests a green-up midpoint of day 164-165 (13-14 June) and a green-up season length of 17-19 days from 10% to 90% greenness (Fig. 7). The senescence midpoint date (Fig. 8) differed somewhat between the two greenness measures, from Sept 4 (percent green) to Sept 9 2013 (excess green), though the rate was similar for both (senescence season of 28-29 days from 90% to 10% of initial greenness).

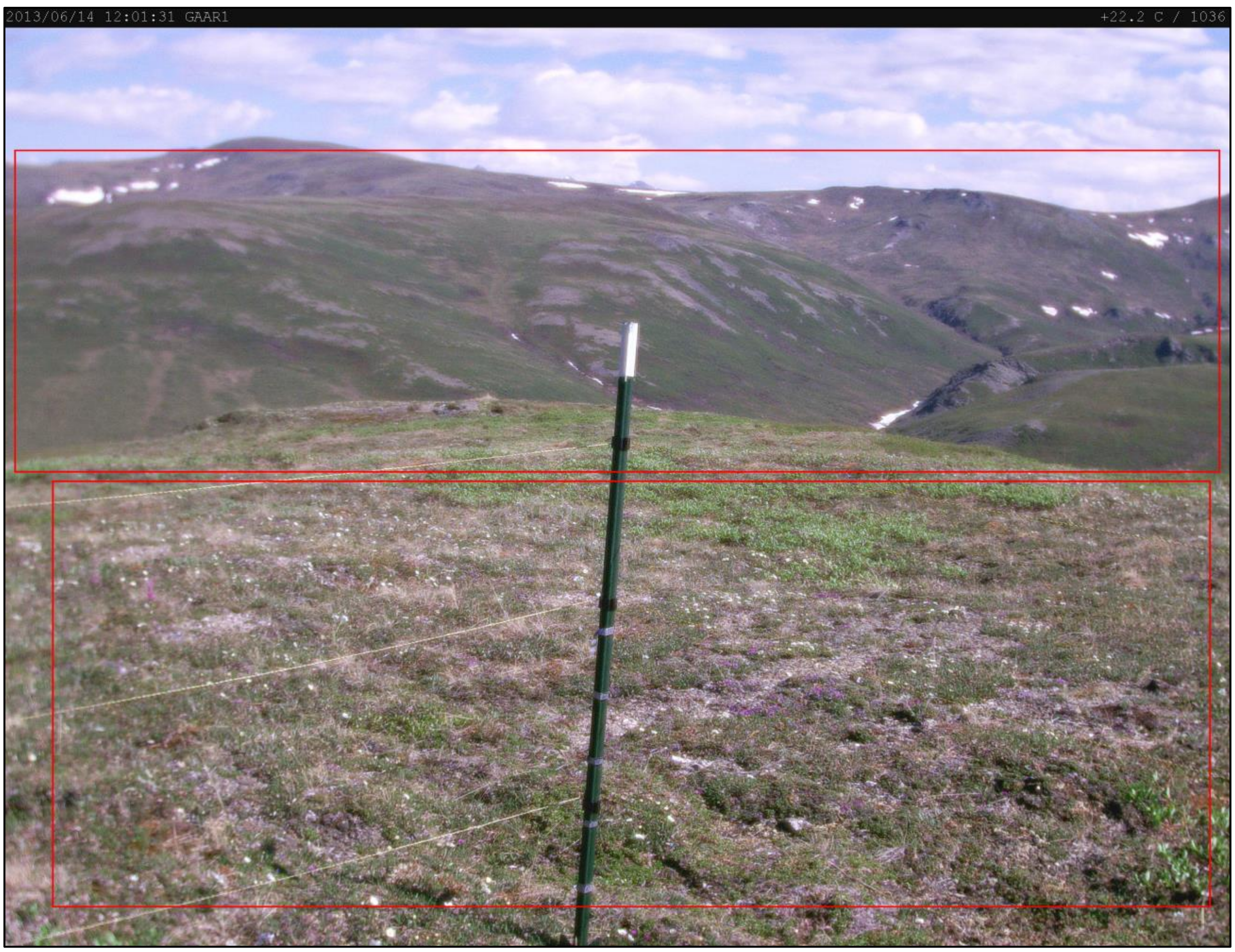

Figure 6. Pamichtuk Lake station phenology monitoring windows, 14 June 2013. This date was identified by the analysis as the midpoint of green-up in the foreground window, while snow cover in the background window was approximately 1%. The background window required an additional mask to remove sky, foreground, and the fence post.

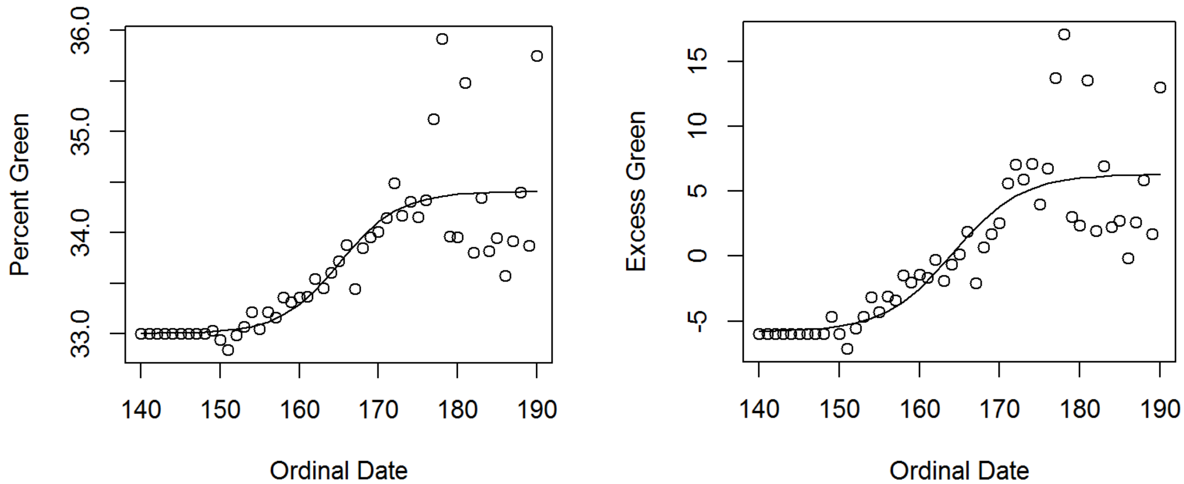

Figure 7. Spring 2013 green-up curve for Pamichtuk, foreground window. The record began on day 149, near the start of green-up but too late to establish a good starting level for the sigmoid curve, so the day 149 value was repeated back to day 140. The fitted curves have parameters a = 33.0, b = 1.40, c = 0.265, d = 165.1, r^2 = 0.66 (percent green, left) and a = -5.82, b = 12.1, c = 0.233, d = 164.2, r^2 = 0.72 (excess green, right). The r^2 values would have been lower with real data for days 140-148.

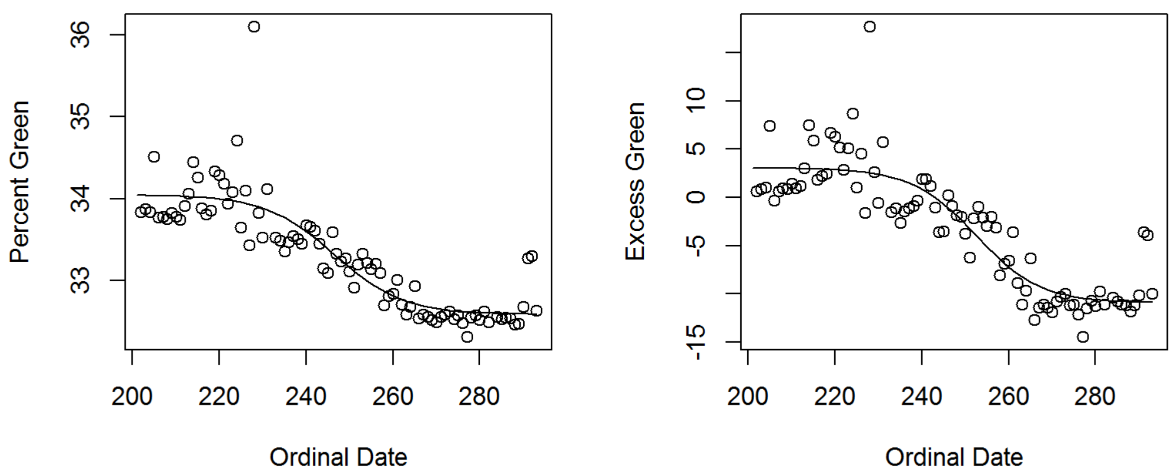

Figure 8. Fall 2013 senescence curve for Pamichtuk Lake, foreground window. The fitted curves have parameters a = 34.0, b = -1.46, c = 0.126, d = 246.5, r^2 = 0.76 (percent green, left) and a = 3.04, b = -13.9, c = 0.135, d = 252.5, r^2 = 0.79 (excess green, right).

Snow

The camera recorded only the end of the melt season in the spring of 2013. At this time the foreground window was snow-free; snow in the background window declined from just over 10% cover on 29 May 2013 to zero by the end of June. The foreground window is nearly level, while the background window is mostly south-facing (Fig. 9). The first snow in the fall came on 3 Sept (in the foreground window only; amounts were too light to register in the background window) and disappeared by the next day. Snow started accumulating again on Sept 19, reaching the 50% threshold on the foreground window. The background window did not exceed the 50% snow cover threshold at this date, due to the lower elevation terrain, windblown areas, and taller vegetation (shrubs) that maintain dark colors above the snow. A thaw reduced the snow cover below 50% in the foreground in mid-October (18-19). Then snow again began accumulating, reaching 50% cover on Oct 20 (foreground) and Oct 24 (background, for the first time this season) and persisted through the end of the record (7 Nov 2013).

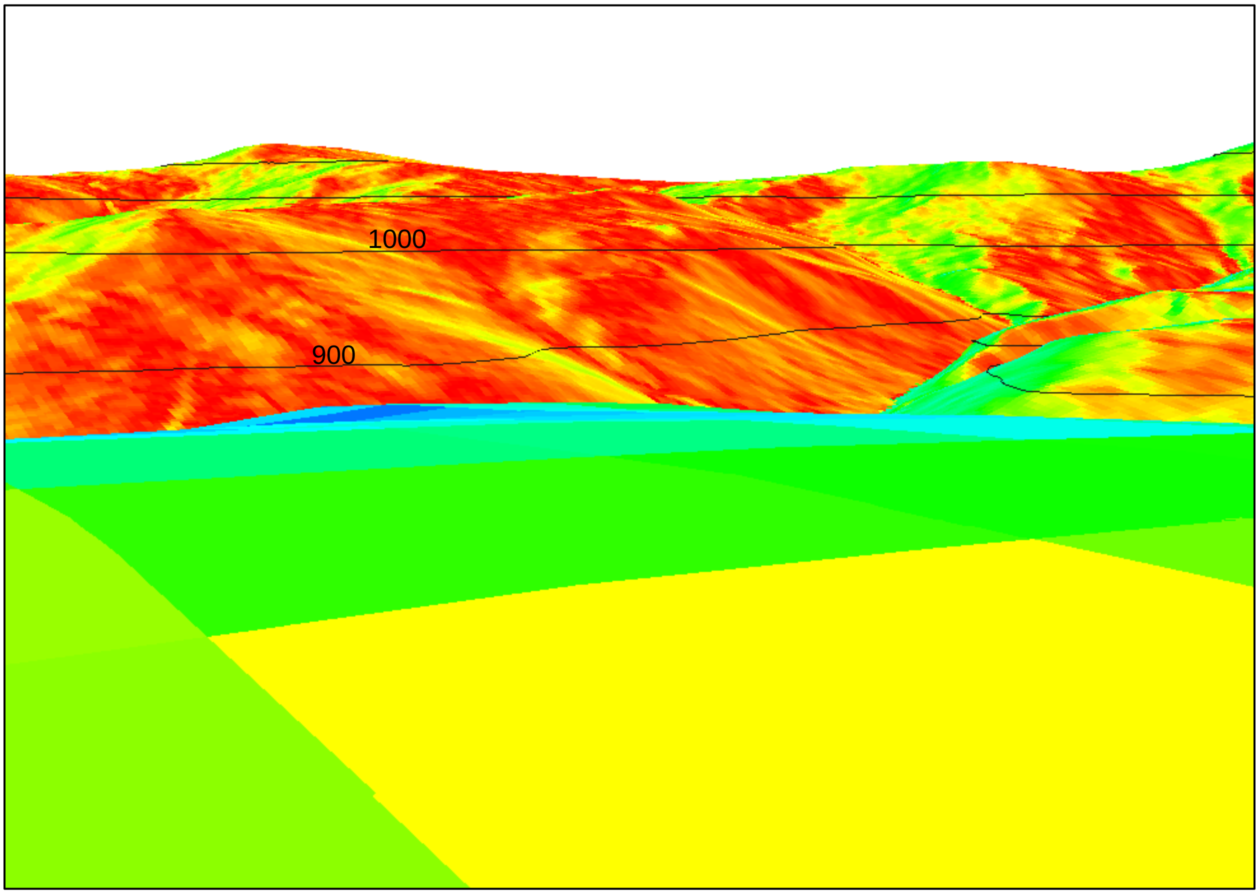

Figure 9. Slope aspects for the Pamichtuk Lake camera view. The color sequence from north to south is blue-green-yellow-red; green and yellow are used on both west (left)-facing slopes and east (right)-facing slopes. The contour lines are elevation in meters at intervals of 100 m. The foreground has a gentle east aspect, and the station elevation is 1019 m.

Salmon River

Greenness

At Salmon River the alder window (Fig. 10) showed rapid senescence (11 and 16 days by the two greenness measures) centered at 3 Sept 2013 (Fig. 11). The tundra window had strong red senescence colors that peaked on the same date (3 Sept; day 246 in Fig. 12).

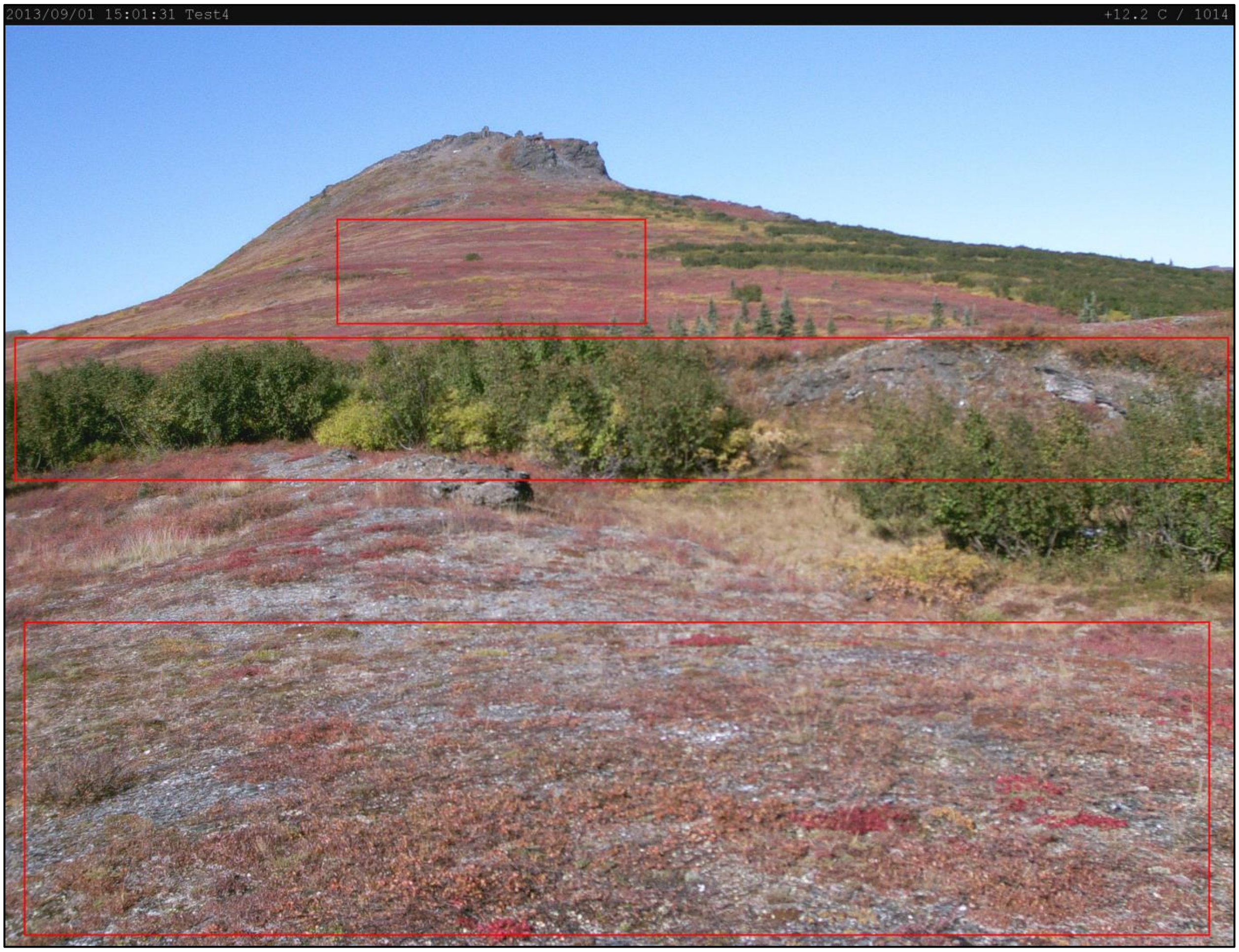

Figure 10. Salmon River station phenology monitoring windows, 1 Sept 2013. The upper window is the “tundra” window, the middle one “alder”, and the lower one “foreground”. This day was 2 days before maximum redness in 2013 for the “tundra” window and the day of maximum rate of change for the “alder” window.

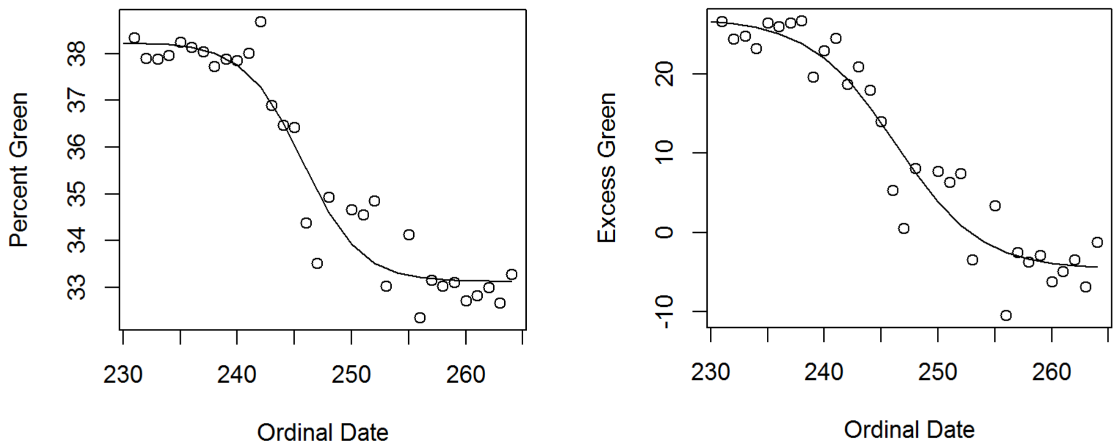

Figure 11. Fall 2013 senescence for the Salmon River station, alder window. The fitted curve parameters are a = 38.2, b = -5.11, c = 0.397, d = 245.7, r^2 = 0.93 for percent green (left) and a = 27.0, b = -31.7, c = 0.268, d = 246.2, r^2 = 0.92 for excess green (right).

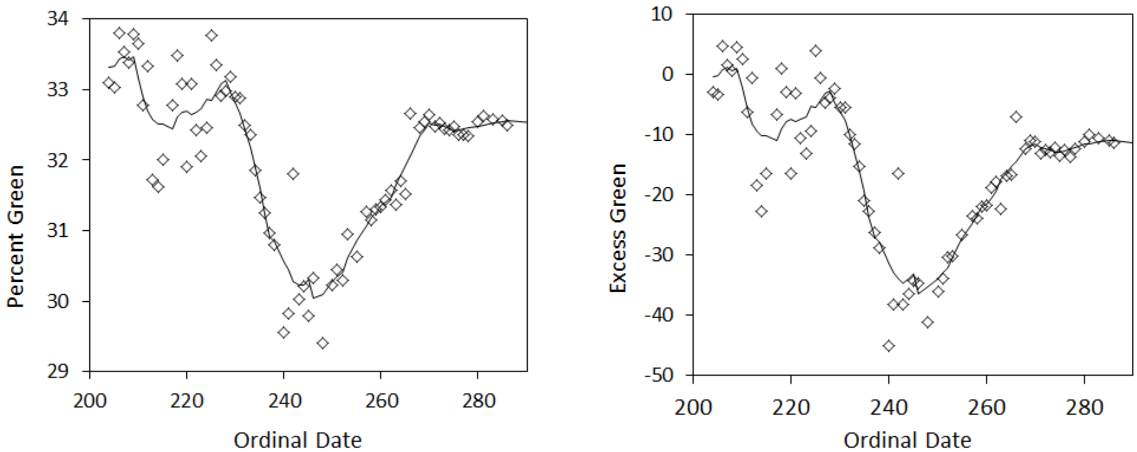

Figure 12. Fall 2013 senescence curves for Salmon River, tundra window, percent green (left) and excess green (right). The daily greenness indices were smoothed by computing a linear regression for a moving 7-day window. The minimum greenness, corresponding to peak of red fall colors, occurred on day 246 (3 Sept) by both greenness indices.

Snow

Snow cover was analyzed in the foreground window only (Fig. 10). This window has a gentle south to southeast aspect (Fig. 13). The first snow arrived on 30 Aug 2013 and was gone the following day. Continuous snow arrived on 23 Sept. The October thaw was not sufficient to break the continuous snow cover here, which persisted until the end of the period of record (17 Nov 2013)

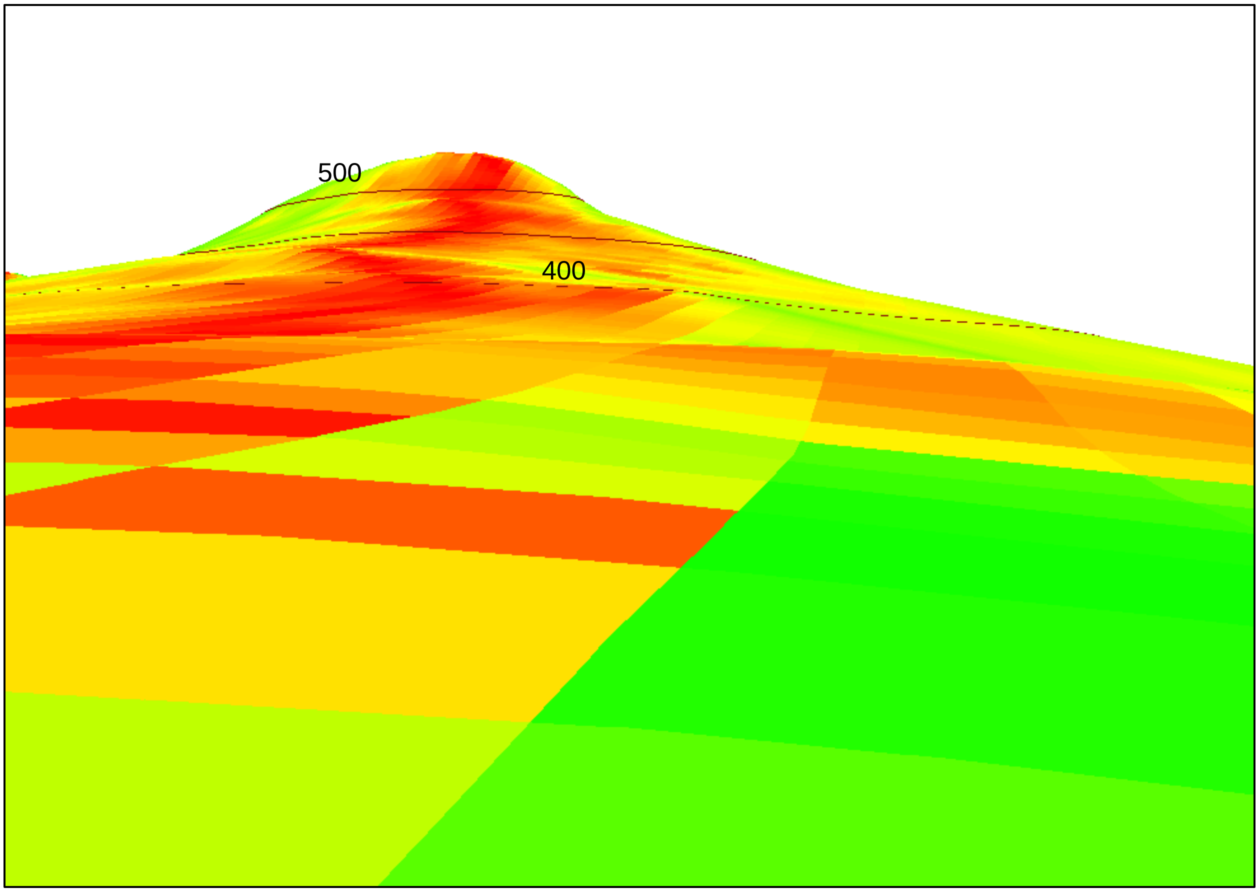

Figure 13. Slope aspects for the Salmon River camera view. The color sequence from north to south is blue-green-yellow-red; green and yellow are used on both west (left)-facing slopes and east (right)-facing slopes. The foreground slopes gently to the southeast. The contour lines are elevation in meters at intervals of 50 m. The station elevation is 381 m.

Serpentine Hot Springs

Greenness

The foreground window at Serpentine Hot Springs was dominated by birch (*Betula nana*) shrubs with strong red senescence colors that peaked on 8 Sept 2013 (Figs. 14-15). Green-up the following spring was centered at 13-14 June 2014 and was 28-29 days long from 10% to 90% greenness (Fig. 16, Table 4). By the end of the day on 13 June 2014 the station had accumulated 173.2 base-0° C degree-days and 25.6 base-5° C degree-days.

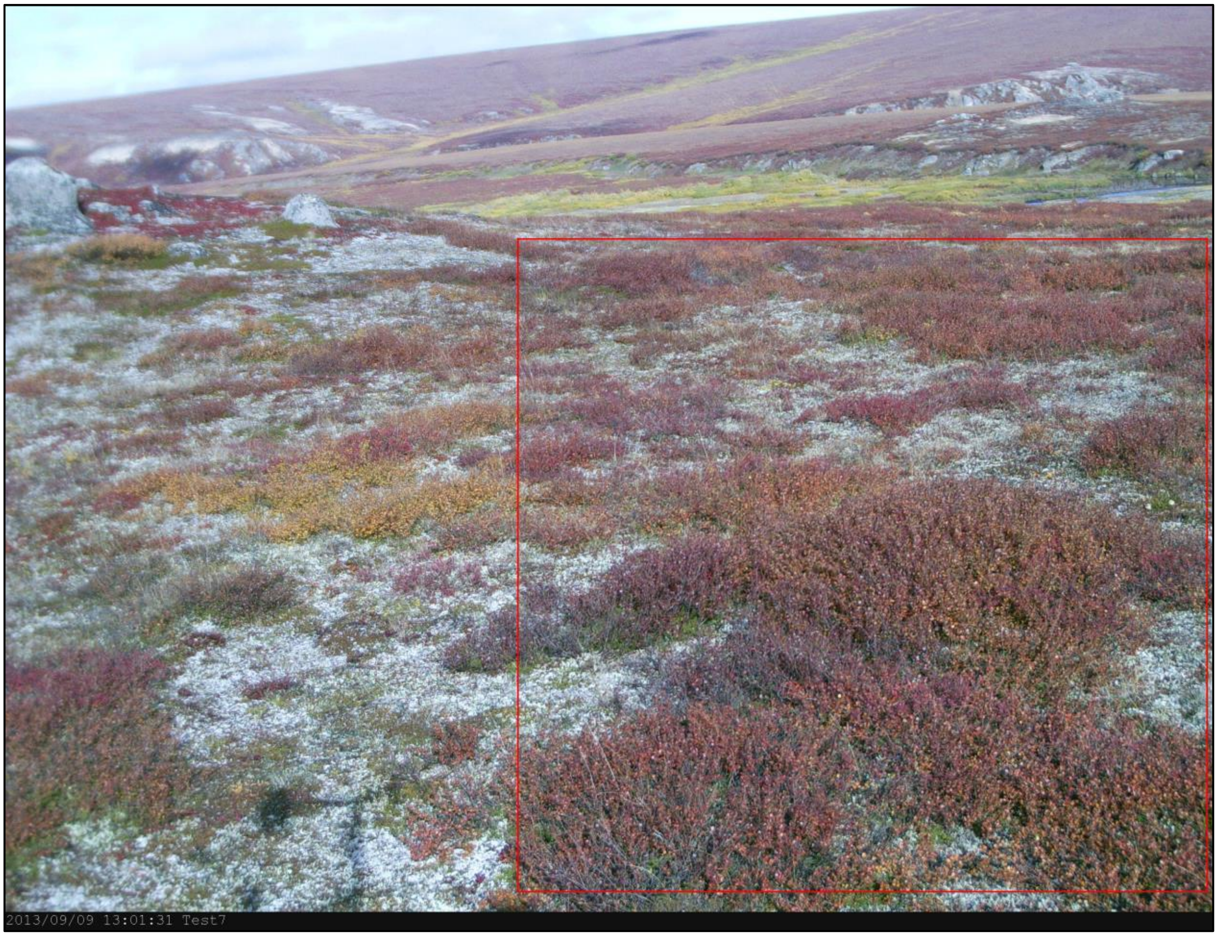

Figure 14. Serpentine Hot Springs station greenness phenology monitoring window, 9 Sept 2013. This was the day of maximum redness in the window. The left side of the foreground was excluded because it was dominated by lichens, which do not change color seasonally.

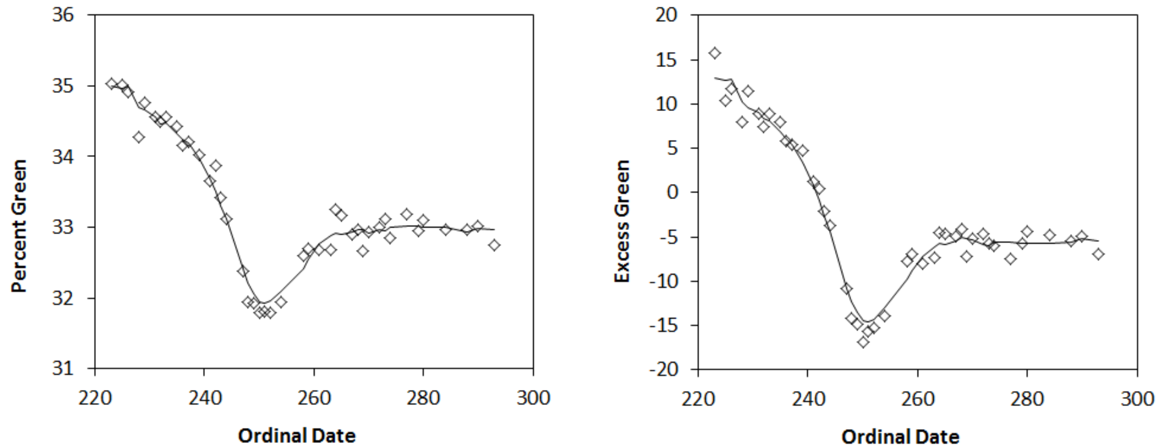

Figure 15. Fall senescence greenness curve for the foreground window at Serpentine Hot Springs, percent green (left) and excess green (right).. The daily greenness indices were smoothed by computing a linear regression for a moving 7-day window. The minimum greenness, corresponding to peak of red fall colors, occurred on day 251 (8 Sept) by both indices.

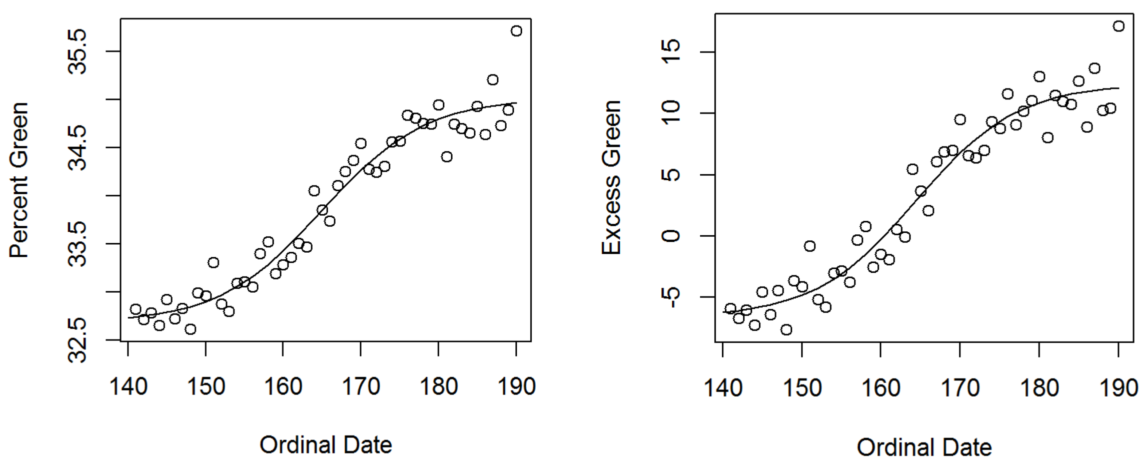

Figure 16. Spring 2014 greenness at Serpentine Hot Springs, foreground window. Curve parameters are a = 32.7, b = 2.34, c = 0.149, d = 165.0, r^2 = 0.94 for percent green (left) and a = -6.63, b = 19.1, c = 0.155, d = 164.5, r^2 = 0.94 for excess green (right).

Snow

Snow cover was analyzed in the same foreground window as greenness phenology, and the background window (Figs. 17-20). The foreground window is nearly level, while the background is mainly south-facing (Fig. 21). The first snow accumulated on 30 Aug 2013 and melted that same day. Several September and October snowfalls failed to persist, and the final image from the month of October (27 Oct) was completely snow-free. The final 2013 photo (7 Nov) had a thin snow cover. When photographs resumed in late January (27 Jan 2014), a patchy snow cover with less than 50% cover was present; it decreased slightly by 1 February 2014 and then persisted with little change through February. Our next photos in early March (6 March) showed a continuous snow cover that persisted through April.

The snow cover measurements show excellent consistency between dates and good fit to a sigmoid curve (Fig 19). The center of the snow loss season was similar for the foreground and background windows (25 and 22 April, respectively), but the rate constant differed. Snow loss was over twice as fast in the foreground, with just 9 days between 90% and 10% snow cover. The background window took 22 days to go from 90% to 10% snow cover; this window included wind-scoured patches that melted out early and persistent snowdrifts.

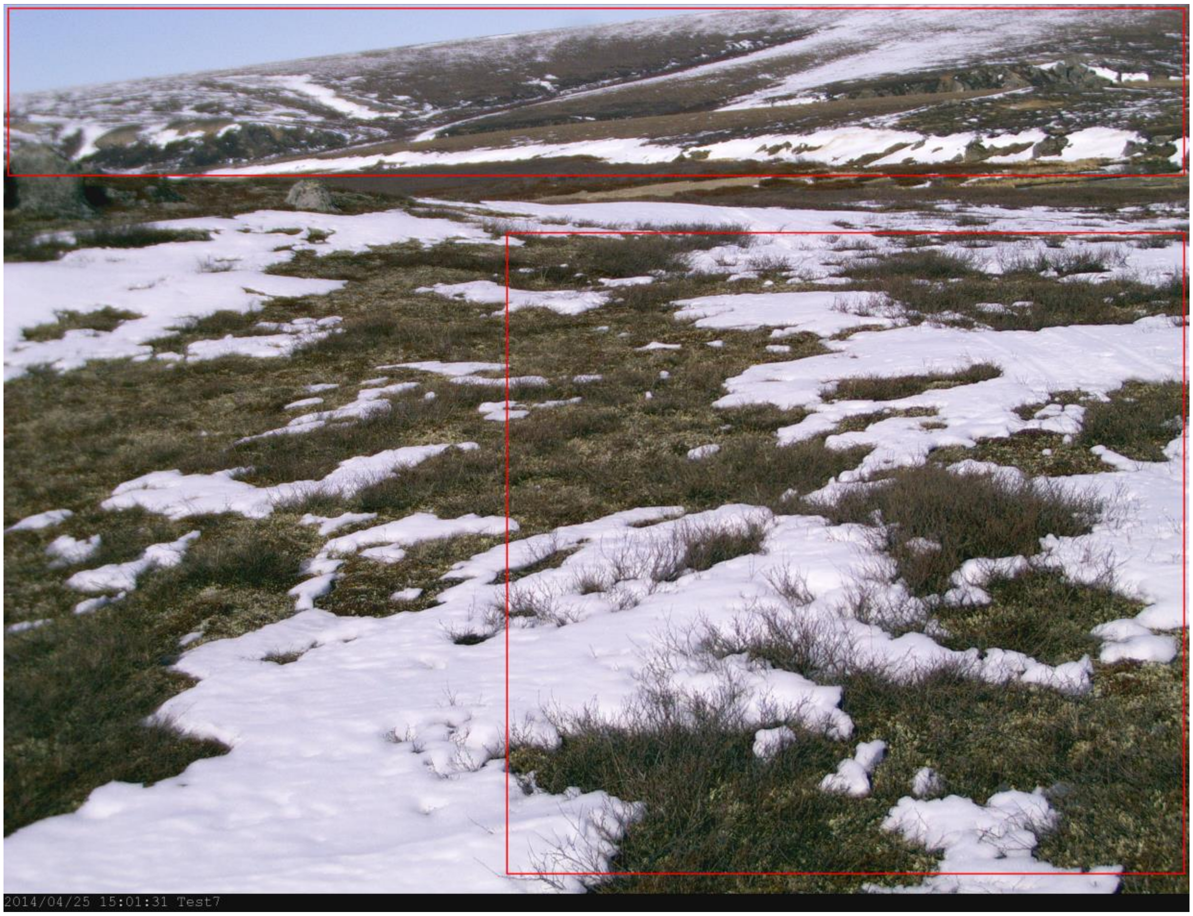

Figure 17. Serpentine Hot Springs station snow phenology monitoring windows, 25 April 2014. The foreground window is the same as that used for greenness monitoring.

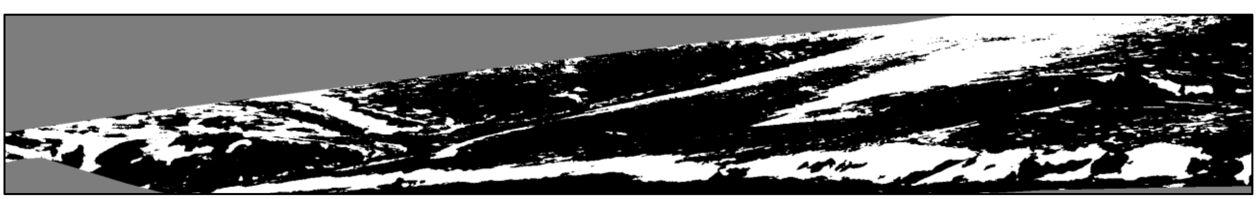

Figure 18. Snow map for the background window at Serpentine Hot Springs, 25 April 2014. The gray areas were unwanted foreground and sky removed by masking. This window had 34% snow cover in this image.

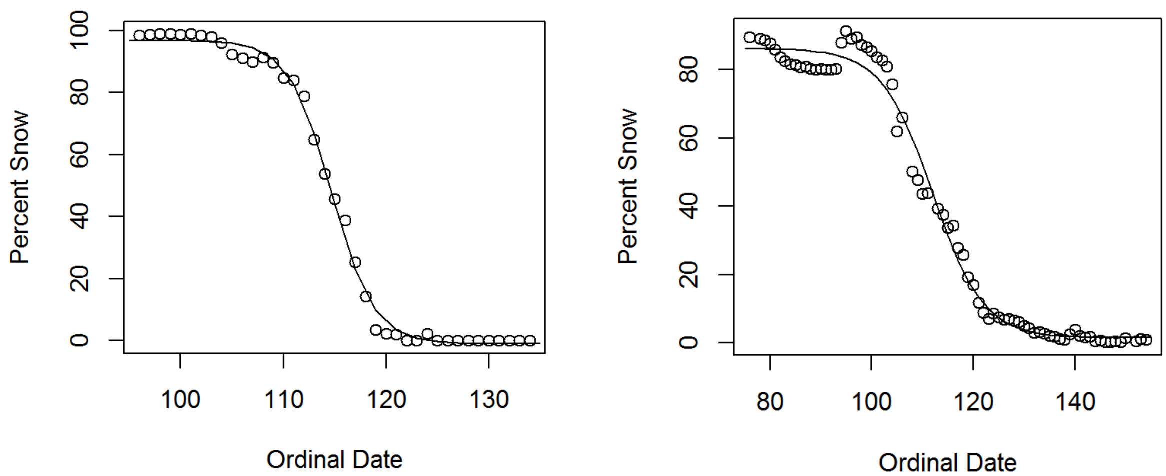

Figure 19. Snow loss curves for Serpentine Hot Springs, foreground window (left) and background window (right). Curve parameters are a = 96.8, b = -97.8, c = 0.481, d = 114.7, r^2 = 0.997 for the foreground window and a = 86.2, b = -84.6, c = 0.200, d = 112.0, r^2 = 0.989 for the background window. Note on the plot of the background window an incipient thaw event around day 80, with new snow on day 94 followed by the main snow loss event.

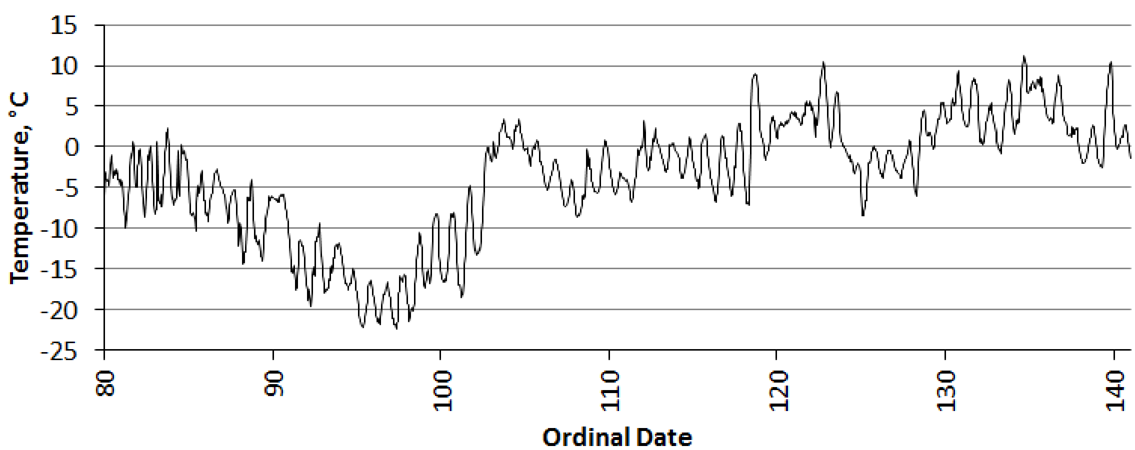

Figure 20. Hourly temperatures at Serpentine Hot Springs during the snowmelt season of 2014.

In both windows, the midpoint of the snow loss curve occurred before any thaw degree-days (0° C base temperature) had accumulated. Comparison of the snow depletion curves with a plot of hourly temperatures vs. time at Serpentine Hot Springs (Fig. 20) shows that most of the snow cover loss in both windows occurred when daily mean temperatures were below freezing and daily highs were from 0 to +3 °C. When persistent above-freezing temperatures arrived on day 118, snow cover was already down to 14% in the foreground window and 26% in the background window. The remaining snow in the foreground was gone by day 122, while deep drifts in the background window (with low percent cover) persisted longer. The last drift did not completely disappear until day 155 (4 June), when about 126 thaw degree-days had accumulated.

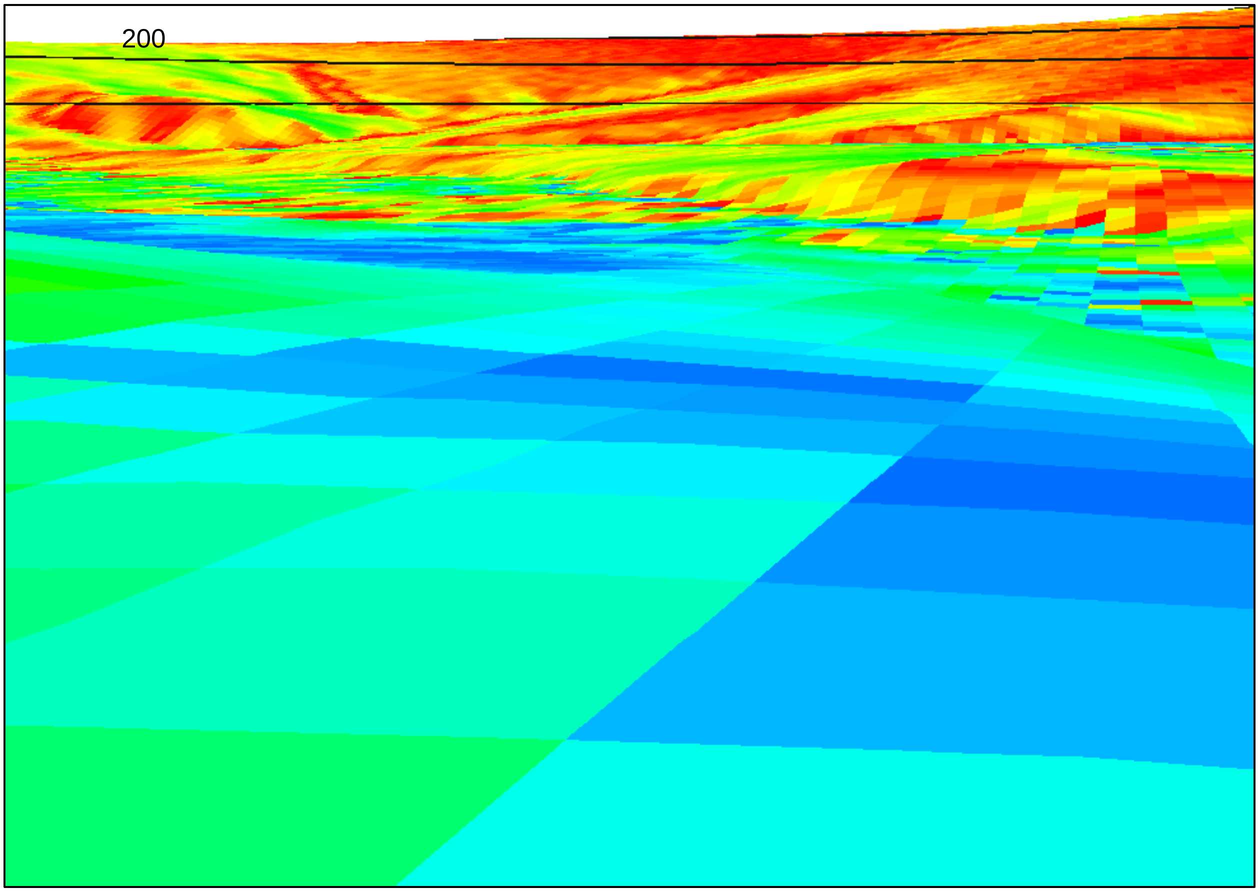

Figure 21. Slope aspects for the Serpentine Hot Springs camera view. The color sequence from north to south is blue-green-yellow-red; green and yellow are used on both west (left)-facing slopes and east (right)-facing slopes. The contour lines are elevation in meters at intervals of 50 m. The station elevation is 150 m.

Discussion

Sigmoid curves fit well to plots of the greenness indices of vegetation vs. ordinal date during green-up at the one site where we had a full spring record (Serpentine Hot Springs 2014). During fall senescence, sigmoid curves fit to greenness vs. ordinal date in windows with *Dryas* dwarf shrub and alder tall shrub vegetation. At the two sites where shrubs with strong red fall colors were present, a distinct fall greenness minimum, corresponding to the redness maximum, was identifiable on the fall greenness curves, and the curves did not have a sigmoid form. The fall greenness minimum (maximum redness) was readily identified on curves smoothed by a moving 1-week linear regression.

The two greenness indices used (percent green and excess green) yielded similar dates for the phenology events. The midpoint of green-up (2 stations), senescence (3 stations), and maximum redness (2 stations) agreed within 1 day in all except one case. I recommend continued calculation of both indices for the near future, since this involves minimal additional work and neither index has yet shown obvious advantages. Sonnentag et al. (2012) found that percent green was more effective in correcting for variations in scene illumination.

Degree-day sums at the green-up midpoint should be more consistent between years and locations than the date of the green-up midpoint, because the former corrects for the timing and intensity of spring warming. More data will allow us to determine if certain vegetation types (such as *Dryas* tundra or dwarf birch tundra) have similar green-up degree-day sums at different sites.

Semi-automated snow cover classification on photos yielded snow percent cover measurements with excellent consistency between consecutive days. The fit to a sigmoid curve was good during the spring snowmelt, though we had data to test from only two analysis areas at one station (Serpentine Hot Springs). Most of the snow cover at Serpentine Hot Springs disappeared during a period of time in late April 2014 when daytime high temperatures were 0 to +3 °C and mean daily temperatures were below freezing. Deep drifts covering a small part of the background analysis window persisted into early June.

Larger capacity batteries will be added to the phenology monitoring cameras in 2015. This should provide a continuous photo record through all seasons. We also plan to install a camera at an additional station in the Noatak National Preserve in 2015.

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